

Into the future with GAIA

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Abstract. The GAIA space observatory was recently approved as Cornerstone 6 of ESA's science program, to be launched no later than mid-2012. It will provide a stereoscopic and kinematic census of about 10^9 stars throughout our Galaxy (and into the Local Group) complete to $V = 20$ mag, amounting to about 1% of the Galactic stellar population. Combined with astrophysical information for each star, provided by on-board multi-colour photometry and (limited) spectroscopy, the positional and radial velocity measurements will have the precision necessary to quantify the early formation, and subsequent dynamical, chemical and star formation evolution of our Galaxy: GAIA will establish when the stars in our Galaxy formed, when and how the Galaxy was assembled, and how the dark matter is distributed. The GAIA data will also allow detection and orbital classification of $\approx 5 \times 10^4$ extra-Solar planetary systems, provide a comprehensive survey of $10^5 - 10^6$ minor bodies in our Solar System, of galaxies in the nearby Universe, of some 5×10^5 quasars, and will test general relativity and cosmology.

1. Structure and Evolution of the Milky Way

The final sentences of Ken Freeman's influential 1987 review of 'The Galactic Spheroid and Old Disk' read: *In this review, I have emphasized studies attempting to elucidate the present dynamical state of the Galaxy. This knowledge is needed before we can hope to proceed with any confidence to the next step: understanding the chain of events that occurred during the formation of the Galaxy.* This next step is the main scientific goal of GAIA¹, an astrophysics mission selected as Cornerstone 6 in the ESA science program (Perryman et al. 2001). A brief look into this future opportunity for Milky Way research is therefore particularly appropriate at this symposium in honor of Ken.

The Milky Way contains a complex mix of stars, planets, interstellar gas and dust, and dark matter. These components are distributed in age (reflecting their birth rate), in space (reflecting their birth places and subsequent motions), on orbits (determined by the gravitational force generated by their own mass), and in chemical element abundances (determined by the past history of star formation and gas accretion). To understand the formation, structure and

¹The acronym has many interpretations, with *Galactic Astrophysics through Imaging and Astrometry* and *Great Advance In Astrophysics* amongst them.

Table 1. GAIA compared with HIPPARCOS

	HIPPARCOS	GAIA
Magnitude limit	12	20–21 mag
Completeness	7.3–9.0	~20 mag
Bright limit	~0	~3–7 mag
Number of objects	1.2×10^5	2.6×10^7 to $V = 15$ 2.5×10^8 to $V = 18$ 1.1×10^9 to $V = 20$
Effective distance limit	1 kpc	1 Mpc
Quasars	none	$\sim 5 \times 10^5$
Galaxies	none	$10^6 - 10^7$
Accuracy	1 mas	4 μ as at $V = 10$ 10 μ as at $V = 15$ 160 μ as at $V = 20$
Broad band	B and V	4-color to $V = 20$
Medium band	none	11-color to $V = 20$
Radial velocity	none	1–10 km/s to $V = 16 - 17$
Observing program	Pre-selected	On-board and unbiased

evolution of our Galaxy therefore requires three complementary observational approaches: (i) a census of the contents of a large and representative part of the Galaxy; (ii) quantification of the present spatial structure, from distances; (iii) determination of the three-dimensional motions. This can be obtained from complementary astrometry, photometry, and radial velocities.

Astrometric measurements uniquely provide model-independent distances (trigonometric parallaxes) and transverse kinematics (proper motions). Multi-color photometry, with appropriate astrometric and astrophysical calibration, provides a measure of extinction, and hence, combined with astrometry, allows derivation of intrinsic luminosities, spatial distribution functions, and stellar chemical abundance and age information. Radial velocities complete the kinematic triad, allowing determination of gravitational forces, stellar orbits, and the distribution of invisible mass. Astrometry and limited photometry from HIPPARCOS, supplemented with ground-based radial velocities, provided this information for $\sim 10^5$ stars in one small part of the Milky Way, the immediate Solar neighborhood. GAIA will provide a representative census of the entire Galaxy in one fell swoop, by repeatedly measuring the positions and multi-color brightness of *all* 10^9 objects to $V = 20$ mag, and radial velocities to $V = 17$ mag (Table 1). The astrometric accuracies will be at the micro-arcsec (μ as) level, and will provide distances to better than 10% well beyond the Galactic Center. Individual stellar motions will be measured even in M31. On-board detection will ensure that variable stars, supernovae, transient sources, micro-lensed events, and minor planets will all be observed and catalogued to $V = 20$ mag.

2. Science with GAIA

The range of scientific topics which will be addressed by the GAIA data is vast, covering much of modern astrophysics, as well as Solar system studies and fundamental physics. A full description can be found in the ESA Concept and Technology Study, available on the GAIA website <http://astro.estec.esa.nl/GAIA>. Documents there contain references to the original work briefly summarized here, as well as details of the many other exciting scientific projects which GAIA will address, but which space precludes discussion of here.

2.1. The stellar halo of the Milky Way

The ESA Concept and Technology study identified many areas of Milky Way research where GAIA will make decisive contributions, including the structure of the Galactic bulge, the determination of the distribution of dark matter, the delineation of spiral structure, the internal dynamical structure of star forming regions and globular clusters, retracing the paths of run-away stars, etc. Here we focus on one such area: the key role of the stellar halo in distinguishing among competing galaxy formation scenarios. The recent review by Freeman & Bland-Hawthorn (2002) covers this topic in great depth.

The stellar halo contains only a small fraction of the total luminous mass of the Galaxy, but the kinematics and abundances of halo stars, globular clusters, and the dwarf satellites contain imprints of the formation of the entire Milky Way. The most metal-deficient stars, with $[\text{Fe}/\text{H}] < -3.5$, represent a powerful tool to understand primordial abundances and the nature of the objects which produced the first heavy elements. The classical picture of inner monolithic collapse, combined with later accretion in the outer Galaxy, predicts a smooth distribution both in configuration and velocity space for our Solar neighborhood. The currently popular theories of hierarchical formation of structure propose that big galaxies are formed by mergers and accretion of smaller building blocks. These events leave signatures in the phase-space distribution of the stars that once formed those systems but are now part of the stellar halo.

In the hierarchical scenario, the current spatial distribution of stars in the inner halo should be fairly uniform, whereas strong clumping is expected in velocity space. This clumping reveals itself in the form of a large number of moving groups (several hundred in a 1 kpc^3 volume centered on the Sun, if the whole stellar halo were built in this way) each having very small velocity dispersion. The required velocity accuracies to detect individual halo streams are less than a few km s^{-1} , requiring measurement precision of order μas . A good way to find such streams is to use the space of adiabatic invariants. Here clumping should be stronger since all stars originating from the same progenitor have very similar integrals of motion, resulting in a superposition of the corresponding streams. In this way, Helmi et al. (1999) found evidence for one halo stream in the HIPPARCOS data, which must have resulted from an accretion about 12 Gyr ago. The future astrometric missions DIVA and FAME will find some additional streams, but it will take the GAIA accuracy, limiting magnitude, and radial velocities to reconstruct the entire set of merged satellites (Helmi & de Zeeuw 2000).

2.2. Stellar Astrophysics

GAIA will provide distances to an unprecedented 0.1% accuracy for 7×10^5 stars out to a few hundred pc, and to 1% accuracy for a staggering 2×10^7 stars up to a few kpc. Distances to better than 10% will reach beyond 10 kpc, and will cover a significant fraction of our Galaxy, including the Galactic Center, spiral arms, the halo, and the bulge, and—for the brightest stars—to the nearest satellites. With the parallel determination of extinction/reddening and metallicities by means of multi-band photometry and spectroscopy, this will provide an extended basis for reading *in situ* stellar and galactic evolution. All parts of the Hertzsprung–Russell diagram will be comprehensively calibrated, from pre-main sequence stars to white dwarfs and all transient phases; all possible masses, from brown dwarfs to the most massive O stars; all types of variable stars; all possible types of binary systems down to brown dwarf and planetary systems; and all standard distance indicators (pulsating stars, cluster sequences, supergiants, central stars of planetary nebulae, etc.). This extensive amount of accurate data will stimulate a revolution in the exploration of stellar and Galactic formation and evolution, and the determination of the cosmic distance scale.

The GAIA large-scale photometric survey will have significant intrinsic scientific value for stellar astrophysics, providing 2×10^7 variable stars of nearly all types, including detached eclipsing binaries, contact or semi-contact binaries, and pulsating stars. The pulsating stars include key distance calibrators such as Cepheids and RR Lyrae stars and long-period variables. Existing samples are incomplete already at magnitudes as bright as $V \sim 10$ mag. The GAIA samples to $V = 20$ will be sufficiently large ($\sim 10^4$ Cepheids, and $\sim 10^5$ RR Lyrae's) to calibrate period-luminosity relationships across a wide range of stellar parameters, including metallicity. A systematic variability search in the entire GAIA survey will also reveal stars in short-lived but key stages of stellar evolution, such as the helium core flash and the helium shell thermal pulses and flashes. Prompt processing will identify many targets for follow-up ground-based studies.

2.3. The star formation history of the Galaxy

A central element of the GAIA mission is the determination of the evolution of the star formation rate, and the cumulative numbers of stars formed, of the bulge, inner disk, Solar neighborhood, outer disk and halo of our Galaxy. This information, together with the kinematic information from GAIA, and complementary chemical abundance information, again primarily from GAIA, provides the full evolutionary history of the Galaxy.

2.4. Binaries and extrasolar planets

Many of the 10^9 stars to be observed by GAIA are not single. A key constraint on double and multiple star formation is the distribution of mass-ratios q . For wide pairs ($> 0''.5$) this follows from the distribution of magnitude differences Δm . GAIA will provide a photometric determination of the q -distribution down to $q \sim 0.1$, covering the expected maximum around $q \sim 0.2$. Furthermore, the large numbers of astrometric orbits will allow derivation of the important statistics of the very smallest (brown dwarf) masses as well as the detailed distribution of orbital eccentricities.

GAIA is very sensitive to non-linear proper motions. A large fraction of all astrometric binaries with periods from 0.03–30 years will be recognized by their poor fit to a standard single-star model. Most will be unresolved, with very unequal mass-ratios and/or magnitudes, but in many cases a photocenter orbit can be determined. For this period range, the absolute and relative binary frequency can be established, with the important possibility of exploring variations with age and place of formation in the Galaxy. Some 10^7 binaries closer than 250 pc will be detected, with much larger numbers still detectable out to 1 kpc and beyond. This binary census will also cover essentially the entire (period, Δm) diagram: the classical ‘area of ignorance’ between the short-period spectroscopic binaries and the long-period visual binaries will finally be mapped.

GAIA’s potential for planet detection was assessed by simulating observations of a homogeneous set of extra-solar planetary systems, to establish the expected sensitivity to the presence of planets and the potential for accurate estimation of orbital parameters, as a function of semi-major axis, period, and eccentricity, and the distance from the Sun. These simulations put the number of astrometric detections of Jupiter-mass planets somewhere between 10,000–50,000, depending on details of the detection and orbital distribution hypotheses. Essentially all Jupiter-mass planets within 50 pc and with periods between 1.5–9 yr will be discovered by GAIA. Photometric detections of planetary transits will also be a natural product of the GAIA photometry.

2.5. Solar System

Solar system objects present a challenge to GAIA because of their significant proper motions, but they promise a rich scientific reward. The minor bodies provide a record of the conditions in the proto-Solar nebula, and their properties therefore shed light on the formation of planetary systems. Discovery and orbital determination of near-Earth objects is a subject of high public interest.

GAIA will detect between 10^5 and 10^6 new asteroids, and obtain precise orbits for them. They will include all near-Earth objects with diameters larger than about 1 km, as well as Trojans of Mars and Venus. The mission will also provide an all-sky search for Kuiper Belt Objects, which should produce about 300 brighter than $V = 20$ mag. These are remnants of the pre-Solar nebula, and form the closest link with disks around young stellar objects.

2.6. Extragalactic astrophysics

GAIA will make unique contributions to extragalactic astronomy, including the structure, dynamics and stellar populations in the Magellanic Clouds and other Galactic satellites, and in M31 and M33, with consequences comparable to those summarized above for the Milky Way. The faint magnitude limit and all-sky coverage allows derivation of the space motions of Local Group galaxies, and studies of large numbers of supernovae, galactic nuclei, and quasars.

Local Group. The orbits of galaxies are a result of mildly non-linear gravitational interactions, which link the present positions and velocities to the cosmological initial conditions. Non-gravitational (hydrodynamic) or strongly non-linear gravitational interactions (collisions, mergers) are sometimes significant. It will be possible to determine reliable three-dimensional orbits for a significant sample of galaxies in the Local Group, in a region large and mas-

sive enough to provide a fair probe of the mass density in the Universe. This provides direct constraints on the initial spectrum of perturbations in the early Universe, on the global cosmological density parameter Ω , and on the relative distributions of mass and light on length scales up to 1 Mpc.

Galaxies. GAIA will provide multi-color photometry with $\sim 0''.3$ spatial resolution for all sufficiently high-surface-brightness galaxies. This allows statistical analysis of the photometric structure and color distribution of the central regions of a complete, magnitude-limited sample of many tens of thousands of galaxies with a resolution not achievable from the ground, and study of the large-scale structure of the local Universe. This naturally complements available redshift surveys, and the deeper pencil-beam studies with large telescopes.

Supernovae. GAIA will detect all point-like objects brighter than $V = 20$ mag, so that supernovae can be detected to a modulus of $m - M \sim 39$ mag, i.e., to $z \sim 0.1$. Simulations show that GAIA will detect over 100 000 supernovae of all types. Of these, the most useful as cosmological-scale distance indicators are the Type Ia supernovae, whose light curves are very accurate distance indicators. Rapid detection of such transient sources will allow detailed ground-based determination of lightcurves and redshifts.

Quasars. The astrometry to $V = 20$ mag will provide a census of $\sim 500\,000$ quasars. The mean surface density of $\sim 25\,\text{deg}^{-2}$ at intermediate to high Galactic latitudes will provide the direct link between the GAIA astrometric reference system and an inertial frame. GAIA will be sensitive to multiply-imaged quasars with separations as small as $\sim 0''.2$, which is the regime where most of the lensing due to individual galaxies is expected. Photometric variability of such systems will allow accurate measurement of the Hubble constant, and the entire quasar sample will provide constraints on the cosmological parameters Ω and Λ_0 .

2.7. Fundamental Physics

The dominant relativistic effect in the GAIA measurements is gravitational light bending. Accurate measurement of the parameter γ of the Parametrized Post-Newtonian (PPN) formulation of gravitational theories is of key importance in fundamental physics. Light deflection depends on both the time-space and space-space components of the metric tensor, and has been observed on distance scales of $10^9 - 10^{21}$ m, and on mass scales from $1 - 10^{13} M_\odot$, the upper ranges determined from the gravitational lensing of quasars. GAIA will extend these domains by two orders of magnitude in length, and six orders of magnitude in mass. GAIA will provide a precision of about 5×10^{-7} for γ , based on multiple observations of $\sim 10^7$ stars with $V < 13$ mag at wide angles from the Sun, with individual measurement accuracies better than $10\,\mu\text{as}$. This accuracy is close to the values predicted by theories that assume the Universe started with a strong scalar component, which then relaxed to the general relativistic value with time.

Other possibilities include determination of the solar oblateness, from analysis of suitable asteroid orbits, and limiting any gravitational wave backgrounds, from determinations of coherent jitter in the quasar reference frame. Gravitational waves passing over the telescope will cause a time-varying shift in the apparent position of a source; i.e., the waves cause apparent proper motions which are coherent across the whole sky. GAIA could set, in the $10^{-12} < f < 10^{-10}$ Hz band, the best upper limit on Ω_{gw} .

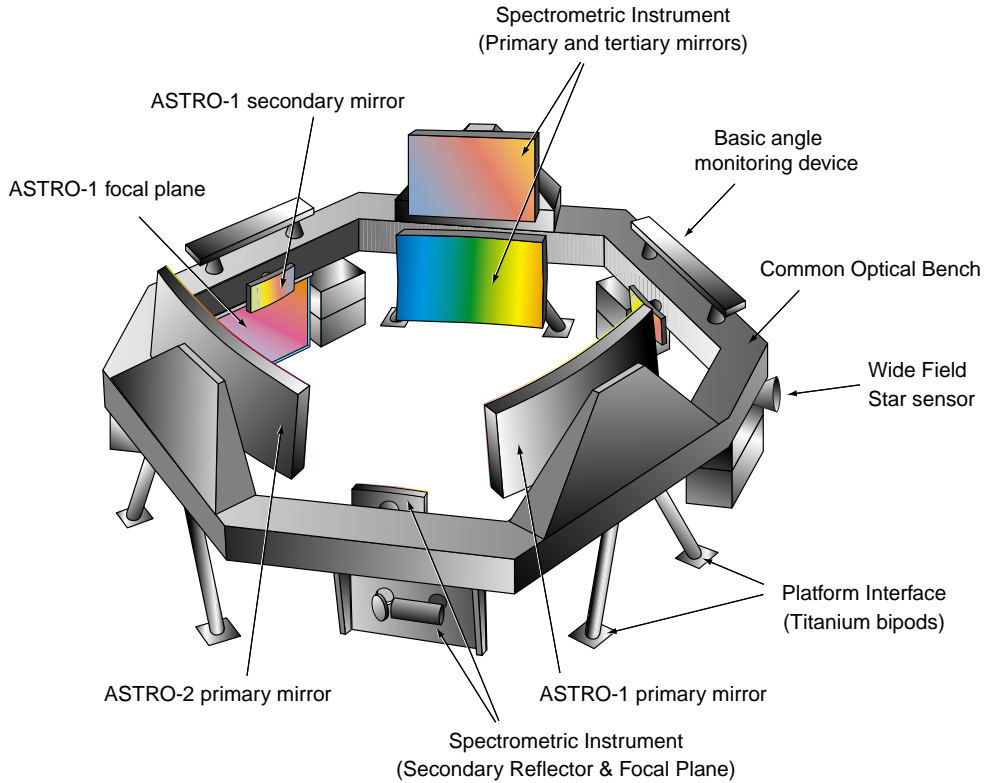


Figure 1. The payload includes two identical astrometric instruments (labelled ASTRO-1 and ASTRO-2) separated by the 106° basic angle, as well as a spectrometric instrument (comprising a radial velocity measurement instrument and a medium-band photometer) which share the focal plane of a third viewing direction. All telescopes are accommodated on a common optical bench of the same material, and a basic angle monitoring device tracks any variations in the relative viewing directions of the astrometric fields.

3. The payload

The proposed GAIA design has arisen from requirements on astrometric precision ($10 \mu\text{as}$ at 15 mag), completeness to $V = 20$ mag, the acquisition of radial velocities, the provision of accurate multi-color photometry for astrophysical diagnostics, and the need for on-board object detection. The result is a continuously scanning spacecraft, accurately measuring one-dimensional coordinates along great circles, and in two simultaneous fields of view, separated by a well-defined and well-known ‘basic’ angle. These one-dimensional coordinates are then converted into the astrometric parameters in a global data analysis which will provide distances and proper motions, as well as information on double and multiple systems, photometry, variability, metric, planetary systems, etc. The payload is based on a large CCD focal plane assembly, with passive thermal con-

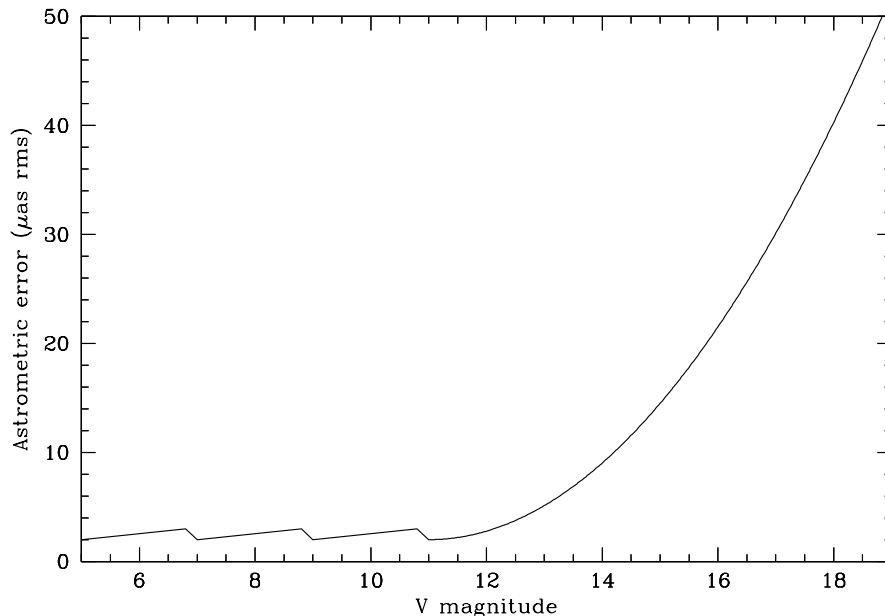


Figure 2. Expected GAIA accuracy versus magnitude (G2V star).

trol, and a natural short-term (3 hour) instrument stability due to a sunshield, the selected orbit, and a robust payload design (Figure 1).

The telescopes are of moderate size, with no specific design or manufacturing complexity. The system fits within a dual-launch Ariane 5 configuration, without deployment of any payload elements. A ‘Lissajous’ orbit at the outer Lagrange point L2 is the preferred operational orbit, from where an average of 1 Mbit of data per second is returned to a single ground station throughout the planned five-year mission. The 10 μ as accuracy target has been shown to be realistic through a comprehensive accuracy assessment program; this remarkable accuracy is possible partly by virtue of the (unusual) instrumental self-calibration achieved through the data analysis on-ground. This ensures that final accuracies essentially reflect the photon noise limit for localisation accuracy: this demanding challenge was proven deliverable by HIPPARCOS. Figure 2 illustrates the expected accuracy as a function of magnitude (Perryman et al. 2001).

4. Data analysis

The total amount of (compressed) science data generated in the course of a five-year mission is about 2×10^{13} bytes (20 TB). Most of this consists of CCD raw or binned pixel values with associated identification tags. The data analysis aims to ‘explain’ these values in terms of astronomical objects and their characteristics by iteratively adjusting the object, attitude and instrument models until a satisfactory agreement is found between predicted and observed data. This will

require expert knowledge from several different fields of astronomy, mathematics and computer science to be merged in a single efficient system, including

- physical modeling of the observations in terms of detectors, optics, satellite attitude and the astrometric and photometric characteristics of the objects, including a fully general-relativistic treatment consistent to the $1 \mu\text{as}$ level;
- accurate geometric and photometric calibration of the instruments, including the celestial orientation (attitude) of the instrument axes;
- efficient procedures for generating and maintaining software, and for the management, processing and dissemination of data.

The ESA Concept and Technology Study considered neural network techniques and object-orientated data structures, and included a detailed assessment of the storage, computational processing and algorithmic demands of the resulting satellite data stream. The simulations have supplied confidence that, while challenging, efficient data reduction is feasible, assuming conservative projections of recent developments in storage devices and computational capabilities.

5. The GAIA Observatory

The GAIA study demonstrated that star selection can be effectively undertaken autonomously on-board, which has the fundamental advantage that GAIA science targets will be complete and unbiased. It also eliminates the need for a complex and costly pre-launch program of observation definition: science operations associated with the mission will also be simplified correspondingly.

Every one of the 10^9 GAIA targets will be observed typically 100 times, each time in a complete set of photometric filters, and a large fraction also with a radial velocity spectrograph. The spatial resolution exceeds that available in ground-based surveys. Source detection happens on-board at each focal-plane transit, so that variable and transient sources are detected. All these complementary datasets, in addition to the superb positional and kinematic accuracy which is derivable from their sum, make GAIA an optimal observatory mission: every observable source will be observed every time it crosses the focal plane.

These data allow studies from asteroids to distant supernovae, from planets to galaxies, and naturally interest almost the entire astronomical community. For this reason, GAIA will be an open observatory mission, directly making available its rich scientific resource to the sponsoring communities. The scale of the GAIA data is such that many analyses can be undertaken during operations, while others will await final data reduction. The GAIA observatory will provide exciting scientific data to a very wide community, beginning with the first photometric observations, and rapidly increasing until the fully reduced GAIA data become available. The resulting analyses will provide a vast scientific legacy.

It is useful to compare GAIA with other astrometric missions. NASA's SIM, to be launched around 2009, will be an interferometer, ideal for precise measurements of a small number of carefully pre-selected targets of specific scientific interest, focussed towards searches for low-mass planets around a few nearby stars, calibration of the distance scale, and detailed studies of known micro-lensing events. FAME, a NASA MIDEX mission, and DIVA, a small German satellite, both to be launched in 2004, are essentially successors to

HIPPARCOS, with an extension of limiting sensitivity, sample size and accuracy by a factor of order 100 in each. They will both substantially improve calibration of the distance scale and the main phases of stellar evolutionary astrophysics, and map the Solar neighborhood to much improved precision. GAIA exceeds these two missions in scale by a further factor of order 100, allowing study of the entire Galaxy, and only GAIA will provide photometric and radial velocity measurements as crucial astrophysical diagnostics.

6. Concluding remarks

GAIA will make it possible to create an extremely precise three-dimensional map of a representative sample of stars throughout our Galaxy and beyond. In the process, by combining positional data with complementary radial velocities, GAIA will map the stellar space motions. Through comprehensive photometric classification, GAIA will provide the detailed physical properties of each star observed: characterizing their luminosity, temperature, gravity, and elemental composition. This massive multi-parameter stellar census will provide the basic observational data to quantify the origin, structure, and evolutionary history of our Galaxy. The result is also of key significance for quantitative studies of the high-redshift Universe: a well-studied nearby template underpins analysis of unresolved galaxies with other facilities, and at other wavelengths.

While challenging, the entire GAIA design is within the projected state-of-the-art: the satellite is being developed in time for launch in 2010. By combining current technology with the demonstrated HIPPARCOS measurement principles, GAIA will deliver an orders of magnitude improvement in our knowledge of our Galaxy, in terms of accuracy, number of objects, and limiting magnitude. With this schedule, a complete stereoscopic map of our Galaxy will be available within 15 years. The successful completion of this program will characterize the structure and evolution of stars and our Galaxy in a manner completely impossible using any other methods, and nearly inconceivable as recently as the time of Ken's 1987 review. This is an excellent prospect to look forward to when considering Ken's 75th birthday celebration!

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References

- Freeman K.C., 1987, *ARA&A*, 25, 603–632
- Freeman K.C., Bland-Hawthorn J., 2002, *ARA&A*, in press
- Helmi A., de Zeeuw P.T., 2000, *MNRAS*, 319, 657
- Helmi A., White S.D.M., de Zeeuw P.T., Zhao H.S., 1999, *Nature*, 402, 53
- Perryman M.A.C., et al. 2001, *A&A*, 369, 339